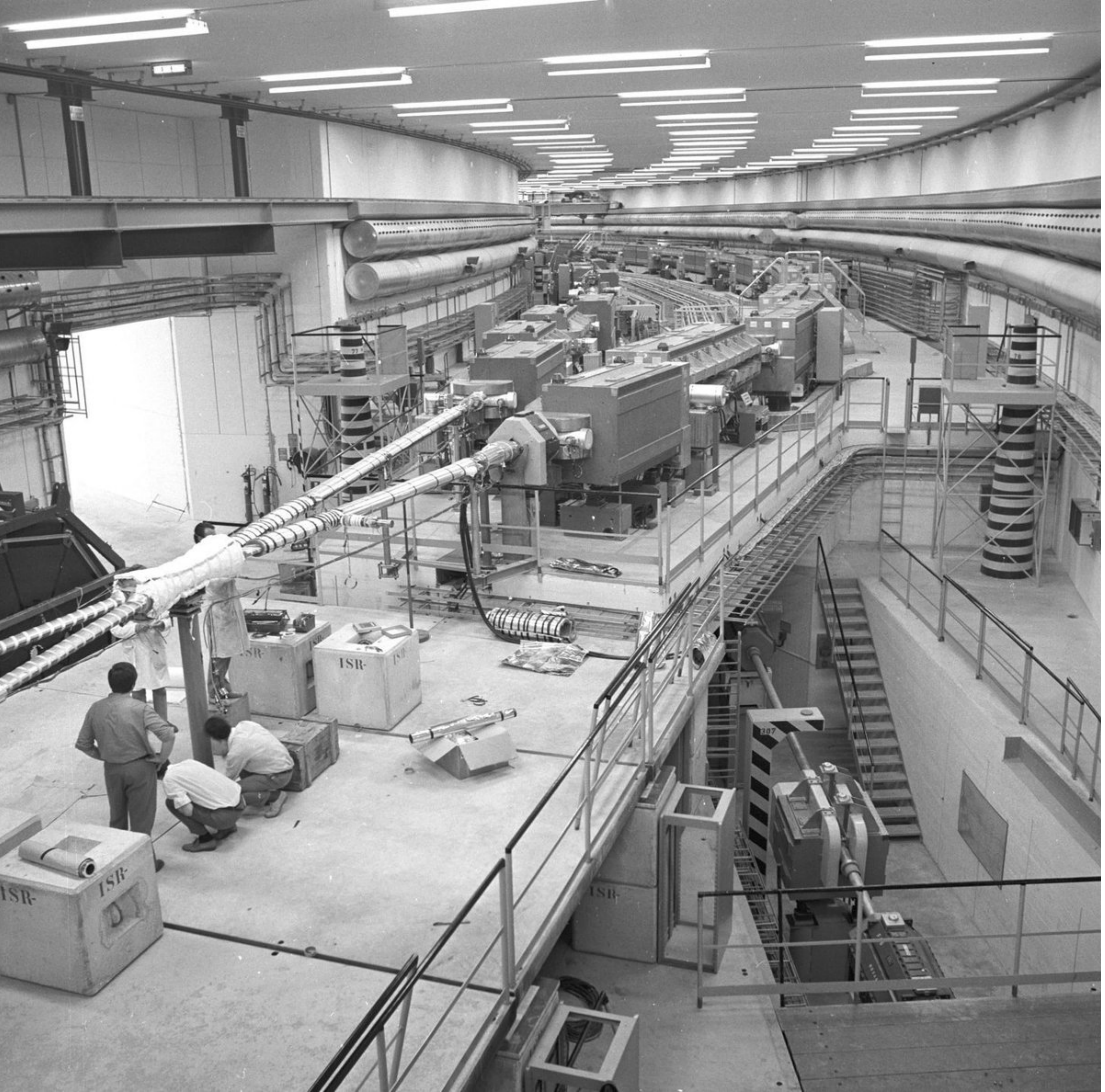
COSMOLOGICAL EXPLANATIONS OF THE HIGGS MASS

Raffaele Tito D’Agnolo



CERN
1971

Higgs Mass Squared

$$m_h^2 |H|^2$$

WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, …

SYMMETRY-BASED ESTIMATE

$$m_h^2 \sim \frac{y_t^2 M_{\mathrm{Pl}}^2}{16\pi^2}$$

Symmetry~10^{34} Experiment

ASSUMPTIONS = SOLUTIONS

1. The Higgs mass is ultimately calculable

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3. We have extrapolated the Planck mass from low energy measurements

4. We have implicitly treated quantum gravity as an ordinary quantum field theory where high energy particles can leave only very specific imprints at low energy.

A LIKELY ACCIDENT

Landscape of Higgs Masses

$$-M_*^2 \leq m_H^2 \leq M_*^2$$

PART 2: A CHANGE OF PERSPECTIVE

Symmetry

$$m_h^2 = 0$$

Is special in the underlying theory of Nature

Landscape

$$m_h^2 = 0$$

Is special just for the evolution of the universe

A NEW OLD IDEA

1998 — Atomic Principle

2003 — Attractor Vacua

2004

A NEW OLD IDEA

Higgs Discovery
2012

1998 — Atomic Principle

2003 — Attractor Vacua

2004

2015 — Relaxion

2016 — NNaturalness

....

OUTLINE

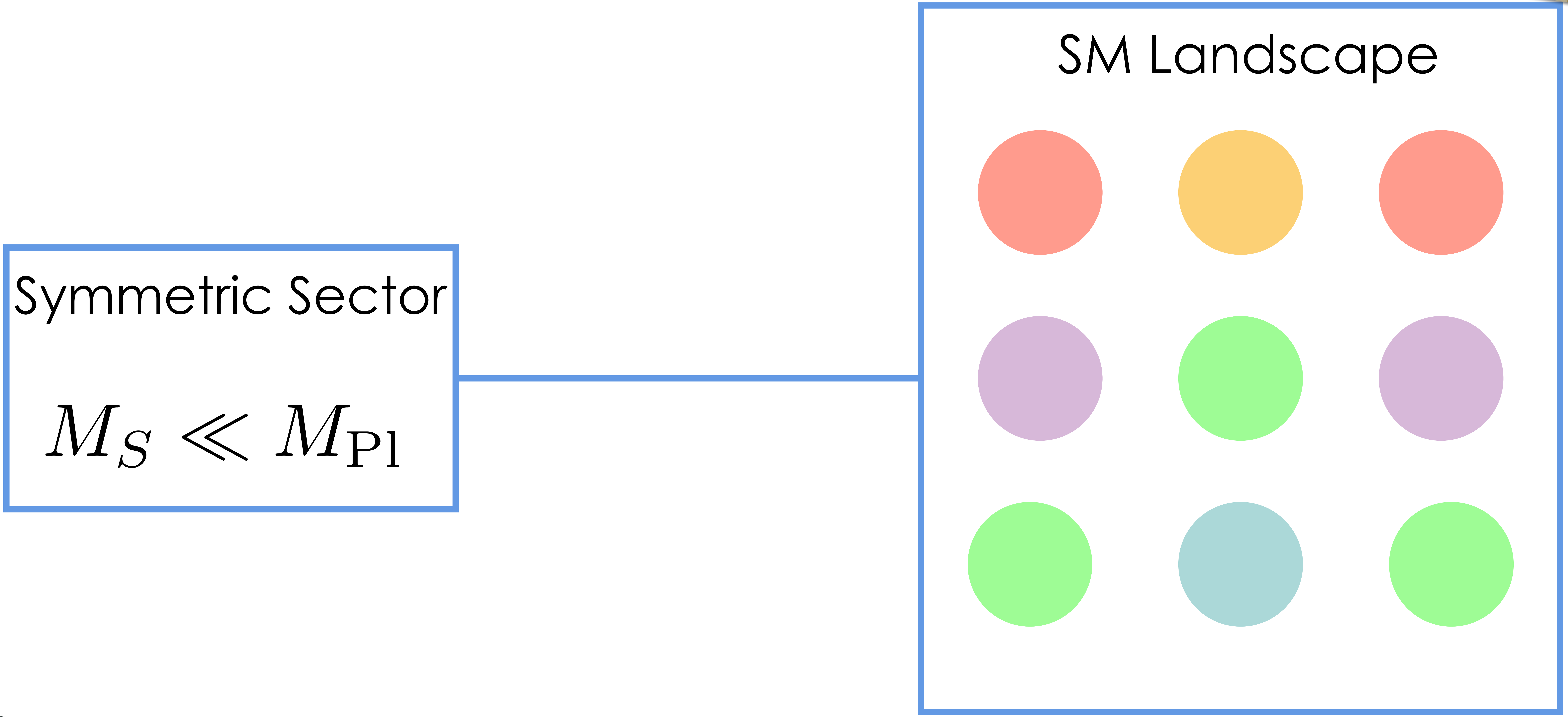
1. Common Structure
2. Examples

Part 2

3. Theoretical Caveats
4. Detection

Part 3

GENERAL STRUCTURE



Symmetric Sector

$$M_S \ll M_{\rm Pl}$$

SM Landscape

An event triggered by the symmetric sector selects the observed

$$m_h^2$$

EXAMPLE 1: ANTHROPIC ARGUMENTS

[Agrawal, Barr, Donoghue, Seckel ’97]

SM Landscape

Symmetric Sector

$$\Lambda_{\mathrm{QCD}} \ll M_{\mathrm{Pl}}$$

$$\mathrm{QCD}$$

$$W_{qq}(x-y)$$

“Friendly”
String Landscape?

[Arakni-Hamed, Dimopoulos, Kachru, ‘05]

EXAMPLE 2: STATISTICAL ARGUMENTS

[Dvali, Vilenkin ’03], [Dvali ’04]

$$F_4 = dA_3$$

$$S \supset \int d^4x\sqrt{-g}\left(\frac{F_4^2}{48} + M_{\mathrm{Pl}}^2(-1 + \frac{F_4^2}{M_{\mathrm{Pl}}^2} + \ldots)|\phi|^2 + \ldots\right) + q(\phi)\int d^3\xi\, A_{\mu\nu\rho}\frac{\partial x^\mu}{\partial \xi^a}\frac{\partial x^\nu}{\partial \xi^b}\frac{\partial x^\rho}{\partial \xi^c}\epsilon^{abc}$$

EXAMPLE 2: STATISTICAL ARGUMENTS

[Dvali, Vilenkin '03], [Dvali '04]

$$q(\phi) = \frac{\phi^N}{M_{\mathrm{Pl}}^{N-2}}$$

$$\Delta\langle\phi\rangle^2 / \langle\phi\rangle^2 \sim \langle\phi\rangle^{N-2}$$

At every step the brane charge is smaller
-> most vacua are at small vev

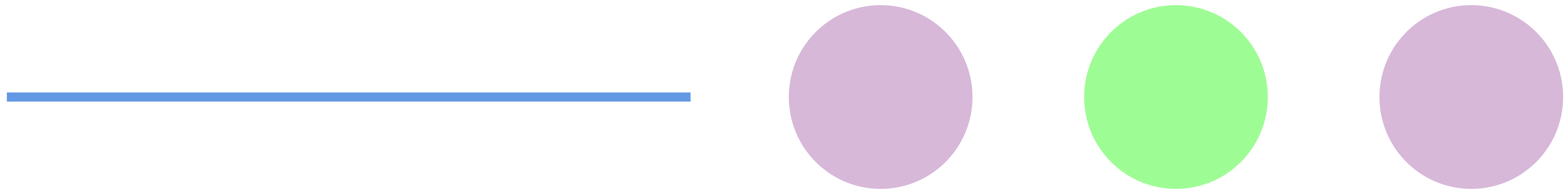
EXAMPLE 2: STATISTICAL ARGUMENTS

[Dvali, Vilenkin ’03], [Dvali ’04]

SM Landscape

Symmetric Sector

$$q(\phi) \lesssim M_{\mathrm{Pl}}^2$$

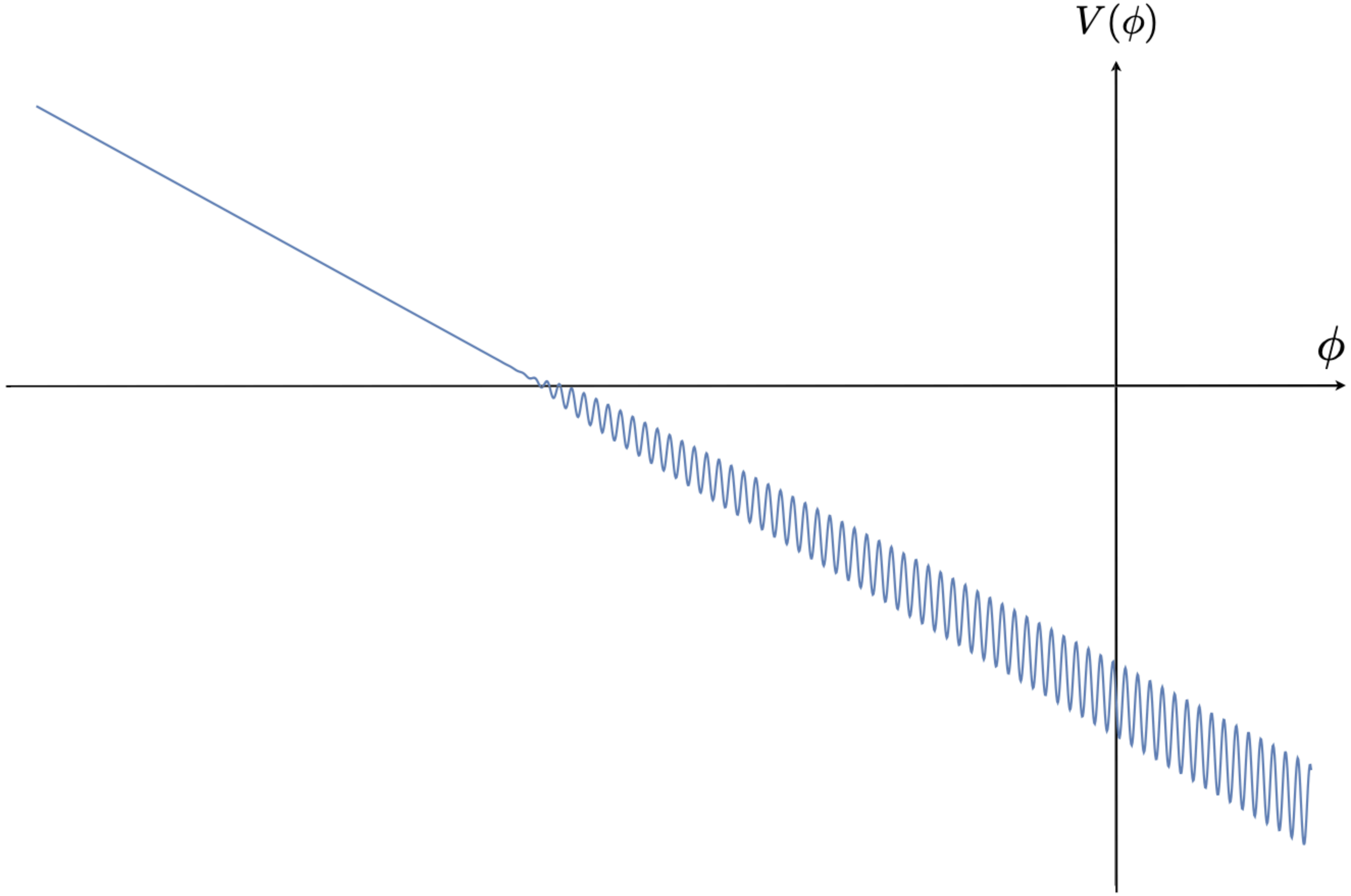


$$A_3 \qquad \frac{\phi^N}{M_{\mathrm{Pl}}^{N-2}} \int_{2+1} A_3 \qquad \frac{F_4^2}{M_{\mathrm{Pl}}^2} |\phi|^2$$

EXAMPLE 3: DYNAMICAL ARGUMENTS

[Graham, Kaplan, Rajendran ’15],

$$V(\phi) = g\phi + ... + (M^2 + g\phi + ...)|H|^2 + \frac{\phi}{f} G\widetilde{G}$$



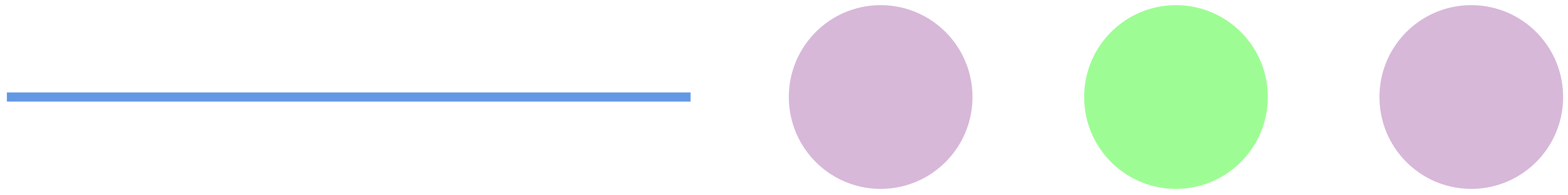
EXAMPLE 3: DYNAMICAL ARGUMENTS

[Graham, Kaplan, Rajendran '15],

Symmetric Sector

$$g \ll M_{\text{Pl}}^3$$

SM Landscape

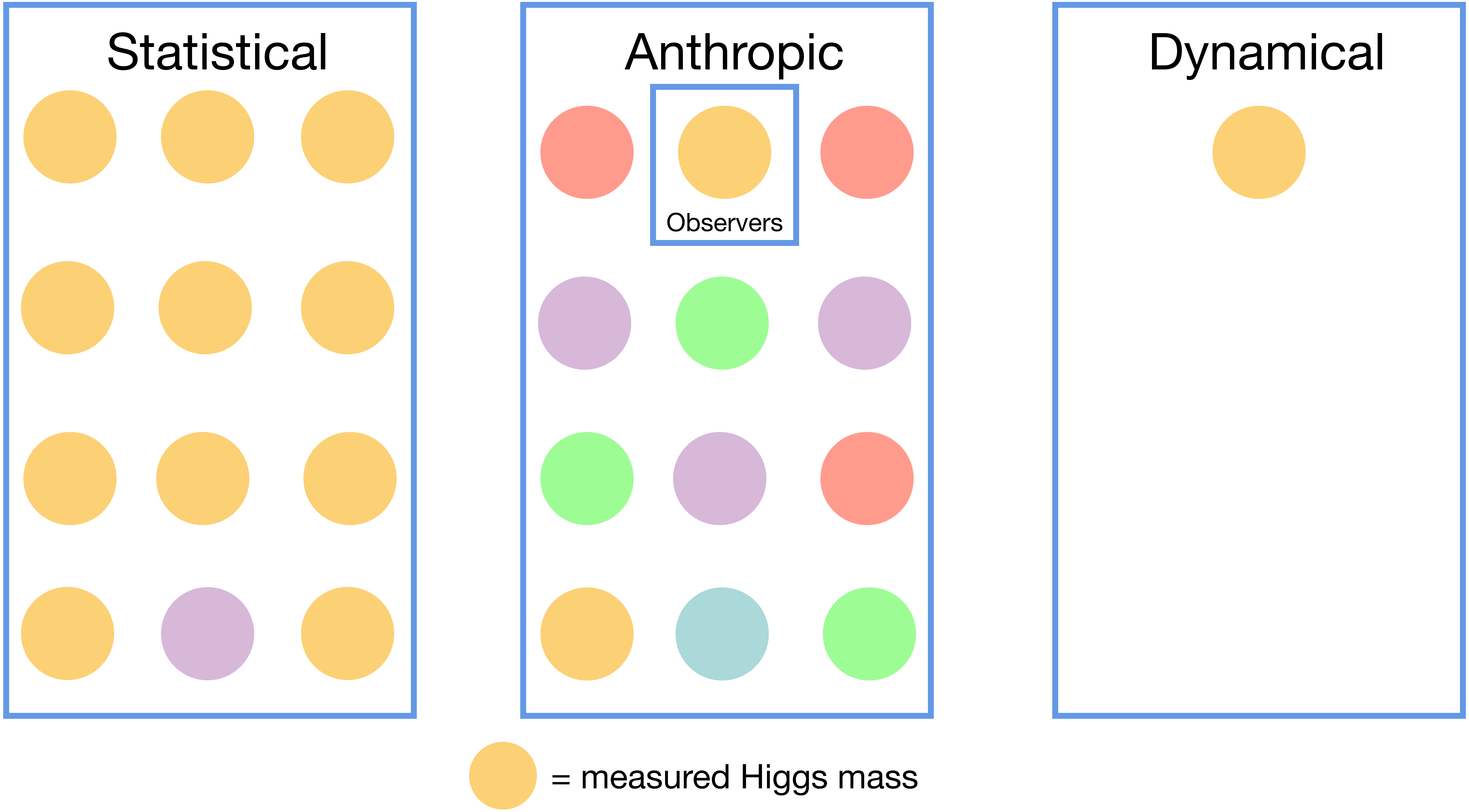


ϕ

$\phi G\widetilde{G}$

$\phi|H|^2$

Landscape at Cosmologically Late Times



Anthropic Selection

[Agrawal, Barr, Donoghue, Seckel '97],[Arvanitaki, Dimopoulos, Gorbenko, Huang, Van Tilburg '16],

[Arkani-Hamed, **RTD**, Kim, '20],

[Giudice, Kehagias, Riotto, '20],

…

Statistical Selection

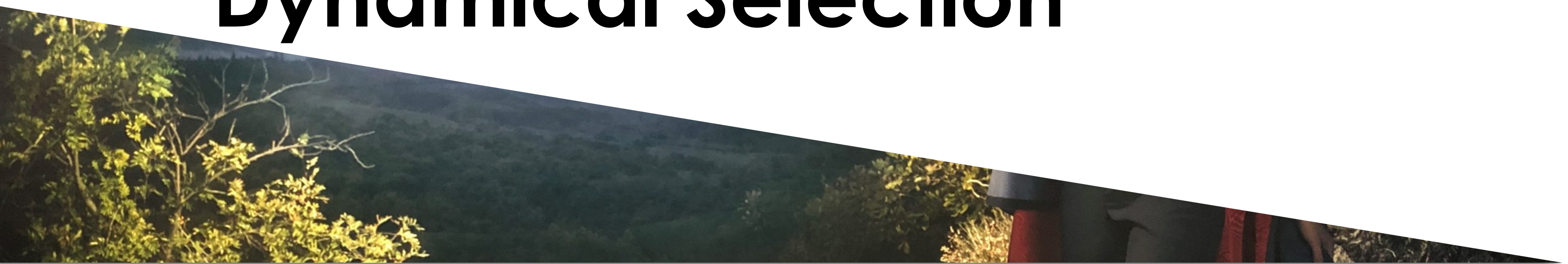
[Dvali, Vilenkin '03], [Dvali '04], [Geller, Hochberg, Kuflik,'18], [Giudice, McCullough, You, '21],

…

Dynamical Selection

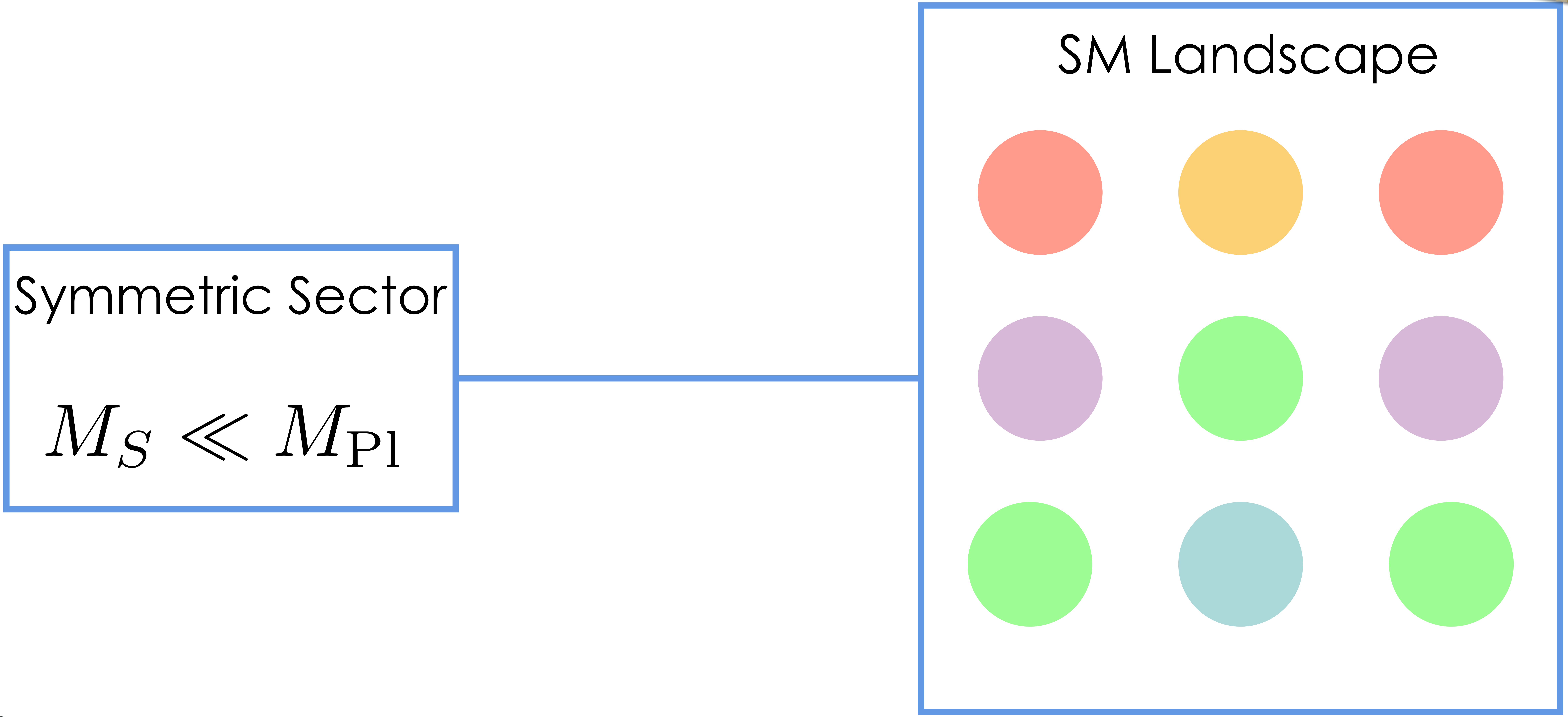
[Graham, Rajendran, Kaplan, '15], [Arkani-Hamed, Cohen, **RTD**, Kim, Pinner, '16], [Csaki, **RTD**, Geller, Ismail, '20], [Strumia, Teresi, '20], [**RTD**, Teresi, '21],

…



PART 3:
BUILD IT AND DETECT IT

GENERAL STRUCTURE

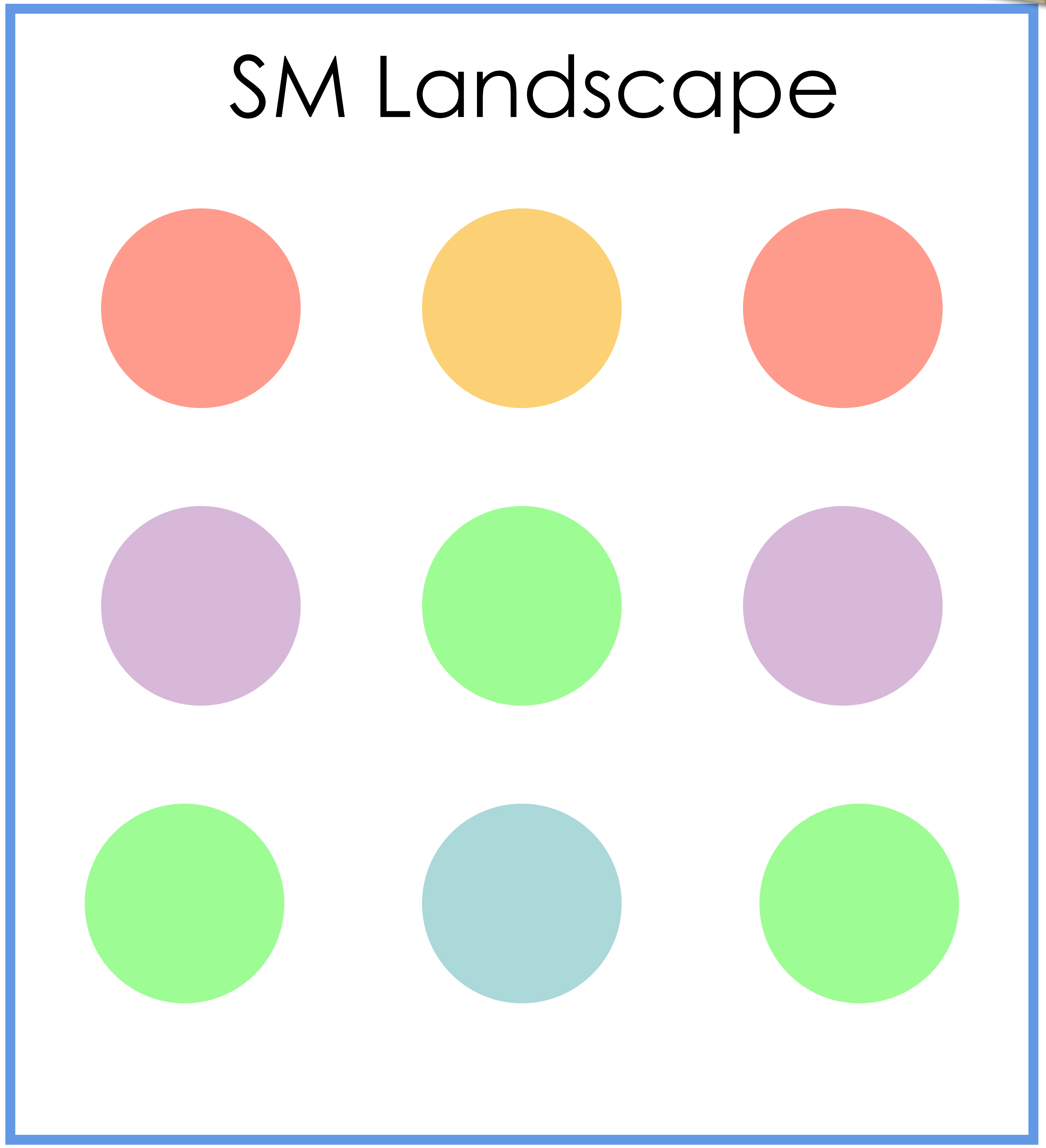


THE LANDSCAPE

1. Multiverse

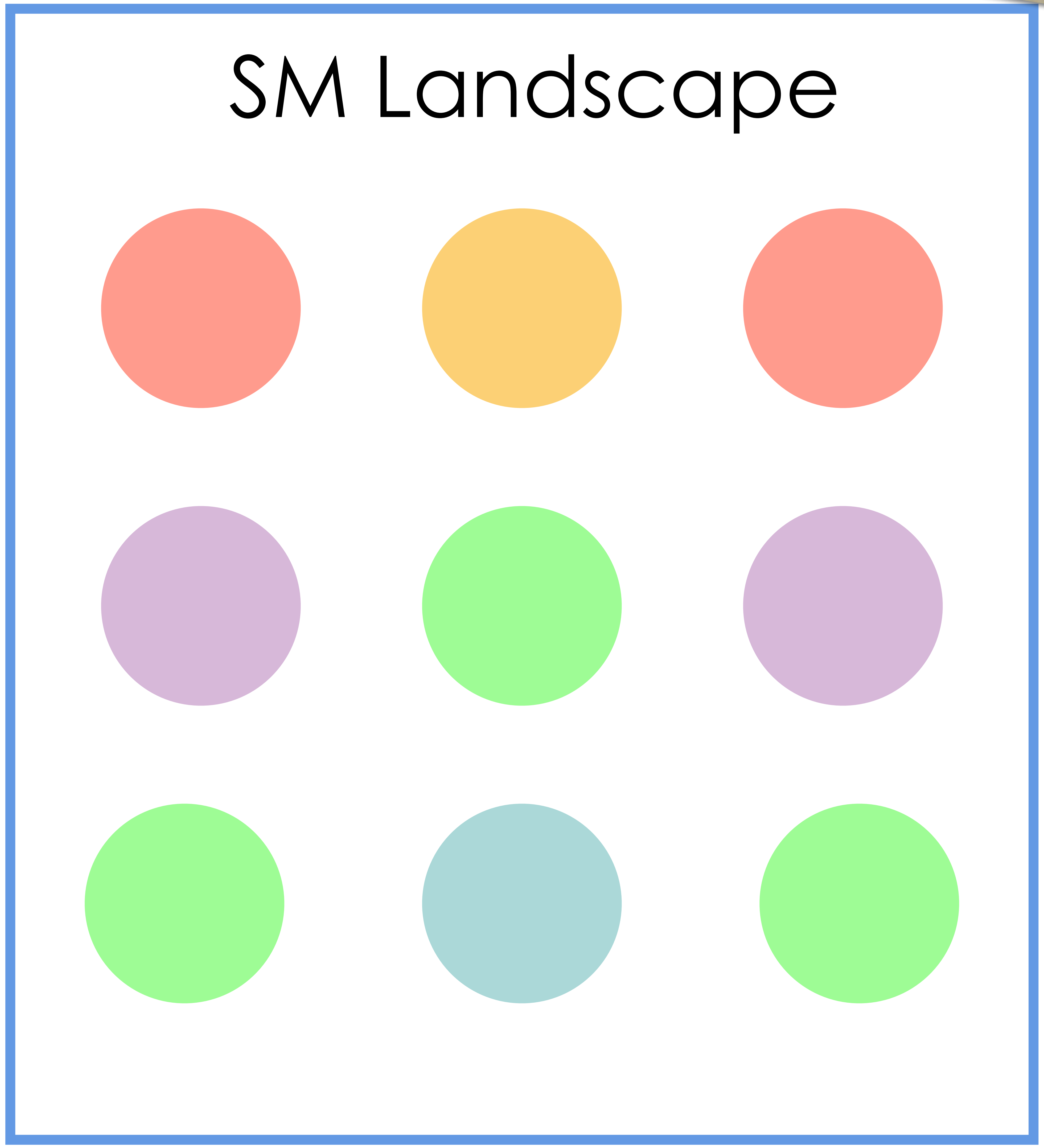
2. Time Series

3. SM Copies



THE LANDSCAPE

1. Multiverse



Caveats on eternal inflation, dS and AdS vacua:

Swampland Program

[Ooguri, Vafa ’06], [Garg, Krishnan ’18],
[Obied, Ooguri, Spodyneiko, Vafa ’18],
[Ooguri, Palti, Shiu, Vafa ’18]

G. Dvali’s Talk

[Dvali ’21],[Dvali, Gomez ’13-’14],
[Dvali, Gomez, Zell ’17], [Dvali ‘20]

THE MULTIVERSE OUTSIDE OF THE SWAMPLAND?

$$V_0(\phi) = \frac{\lambda}{8}\left(\phi^2 - \frac{\mu^2}{\lambda}\right)^2$$

$$\Delta V \equiv V_1(\phi_+) - V_1(\phi_-) = \epsilon V_0(0) = \epsilon \frac{\mu^4}{8\lambda} \simeq \epsilon M_{\mathrm{Pl}}^4$$

THE MULTIVERSE OUTSIDE OF THE SWAMPLAND?

COLEMAN-DE LUCCIA

$$\frac{\Gamma}{V} \simeq M_{\mathrm{Pl}}^4 e^{-27\pi^2 \frac{\sigma^4}{2\Delta V^3} \frac{1}{(1+\bar{\rho}_0^2/4\Lambda^2)^2}}, \qquad \epsilon \ll 40/3$$

THE MULTIVERSE OUTSIDE OF THE SWAMPLAND?

ONE BUBBLE:

$$N_e \simeq \frac{12288\pi^2\lambda}{\epsilon(8+3\epsilon\lambda)^2} + 4\log\frac{H_I}{M_{\rm Pl}} \simeq \frac{10^5}{\epsilon(8+3\epsilon)^2}$$

$$\simeq 34 + N_e$$

ONE TUNED BUBBLE:

$$\simeq 154 + N_e$$

THE MULTIVERSE OUTSIDE OF THE SWAMPLAND?

MODELS OF (NEW) INFLATION WITHOUT SUPER-PLANCKIAN EXCURSIONS:

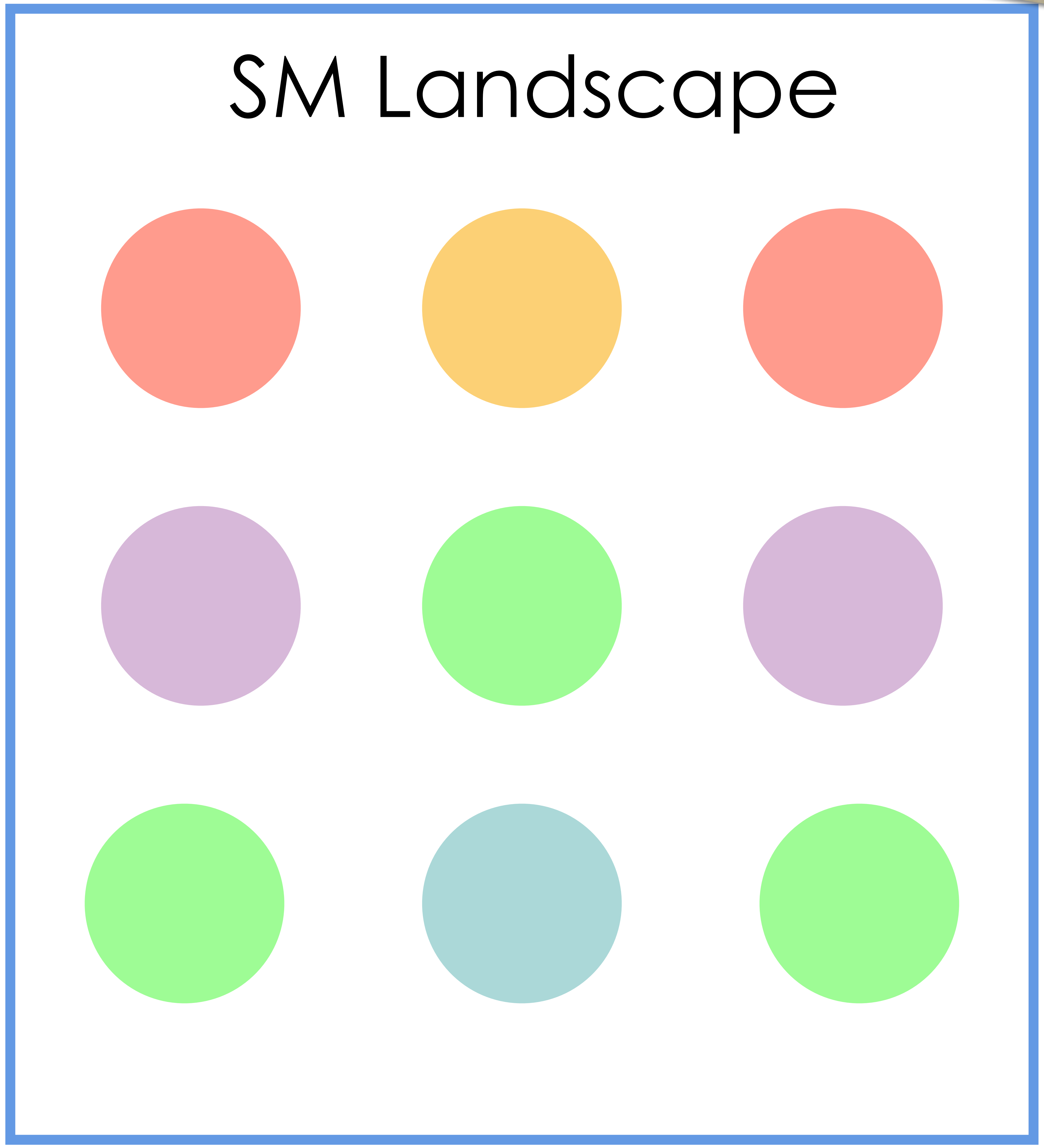
Multi-field inflation [1905.07495], [1906.05772], …
Flat Potentials [1911.09050], …
Particle Production

CAN THEY ACCOMMODATE ENOUGH E-FOLDS?

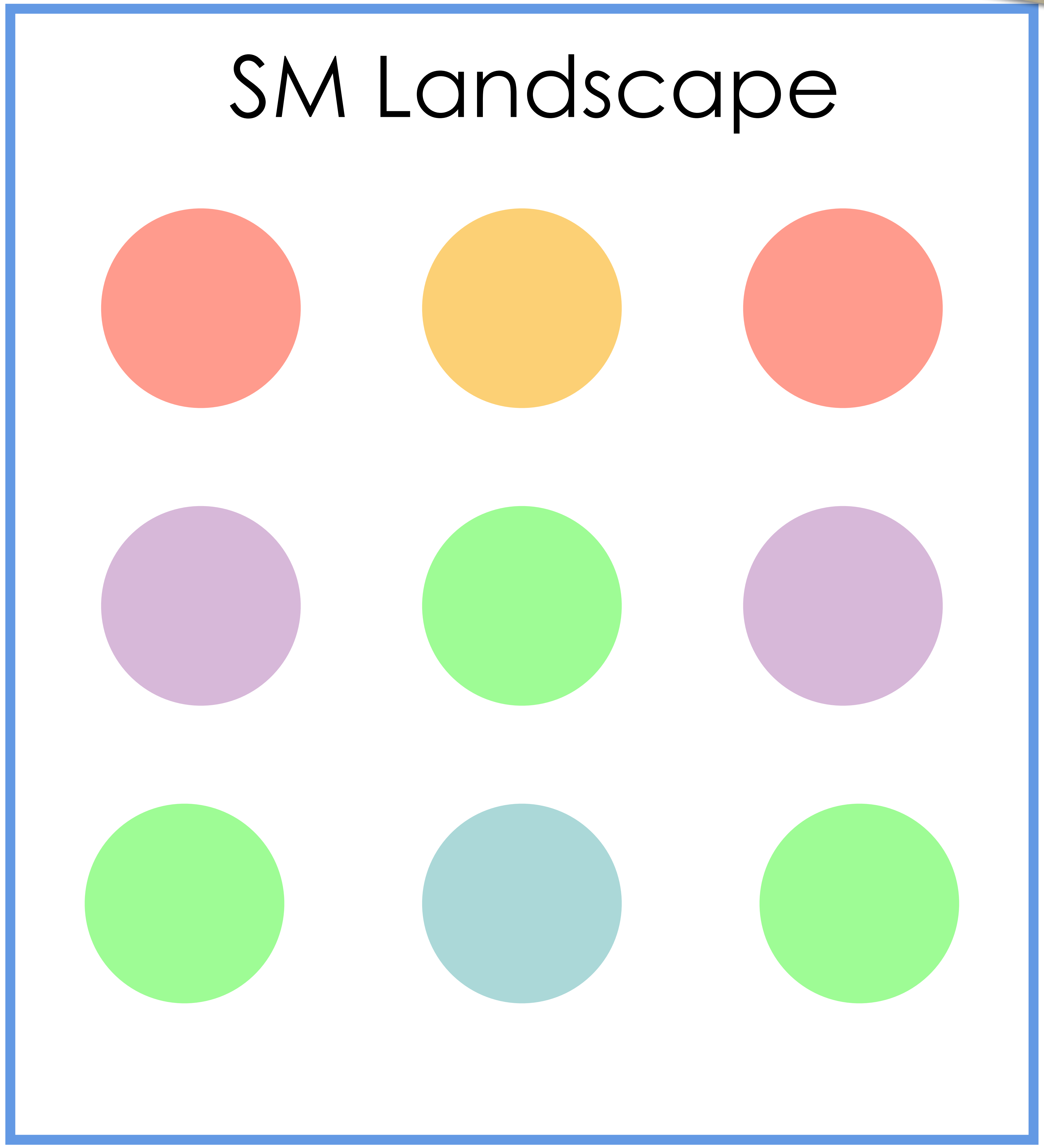
[RTD, G. Rigo, L. Wang, in progress]

THE LANDSCAPE

2. Time Series



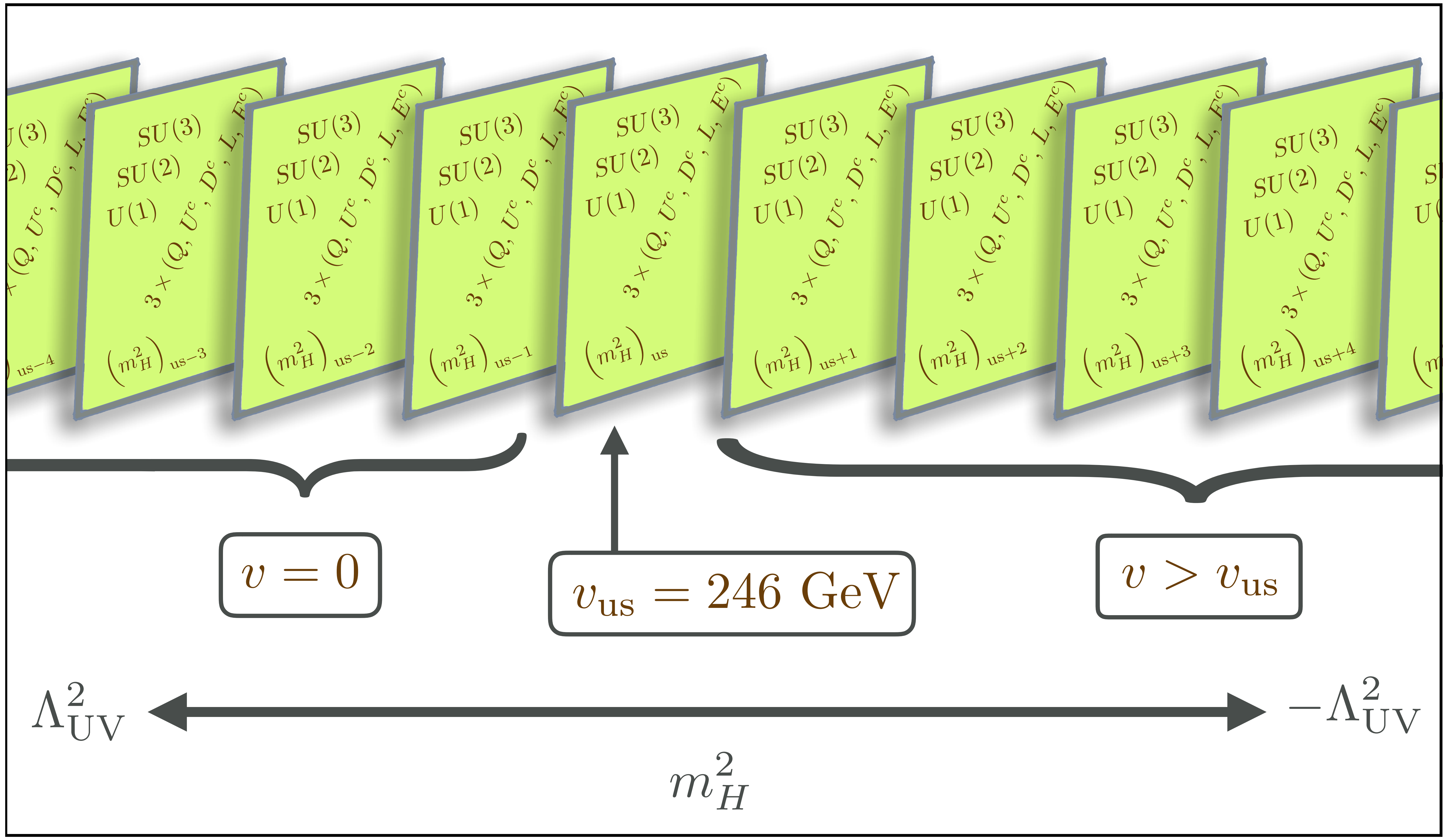
THE LANDSCAPE



3. SM Copies

Nnaturalness

3. SM Copies



[Arkani-Hamed, Cohen, **RTD**, Hook, Kim, Pinner '16]

SYMMETRIC SECTOR

Symmetric Sector

$$M_S \ll M_{\rm Pl}$$

Non-dynamical 4-form

[Dvali, Vilenkin '03], [Dvali '04], [Giudice, Kehagias, Riotto, '20], ...

New Light Scalar ϕ

$$m_\phi \sim v(v/\Lambda_H)^n$$

[Graham, Rajendran, Kaplan, '15], [Arkani-Hamed, Cohen, RTD, Kim, Pinner, '16], [Csaki, RTD, Geller, Ismail, '20], [Strumia, Teresi, '20], [RTD, Teresi, '21],

[Geller, Hochberg, Kuflik,'18], [Giudice, McCullough, You, '21]

...

SYMMETRIC SECTOR

$$m_\phi \sim v(v/\Lambda_H)^n$$

SYMMETRIC SECTOR

$$m_\phi \sim v(v/\Lambda_H)^n$$

$$V_\phi \supset m_\phi^2 M_*^2 \left(\frac{\phi}{M_*}\right)^m$$

$$V_{\langle H \rangle \phi} \simeq \mu^2 M_*^2 \left(\frac{\phi}{M_*}\right)^n \frac{\tilde{v}^{2q-j} \langle h \rangle^j}{\Lambda_H^{2q}}$$

SYMMETRIC SECTOR

$$\frac{V(\phi)}{V_{\phi H}(\phi, v)} \simeq 1$$

Selects the observed Higgs mass

Notable exception: **SOL** [Giudice, McCullough, You, '21]

SYMMETRIC SECTOR

$$\frac{V(\phi)}{V_{\phi H}(\phi, v)} \simeq 1$$

$$\frac{m_\phi^2}{\mu^2} \simeq \frac{\tilde{v}^{2q-j} v^j}{\Lambda_H^{2q}} \lesssim \frac{v^{2q}}{\Lambda_H^{2q}}$$

SYMMETRIC SECTOR

$$\frac{V(\phi)}{V_{\phi H}(\phi, v)} \simeq 1$$

Turns on at one of the SM phase transitions

SYMMETRIC SECTOR

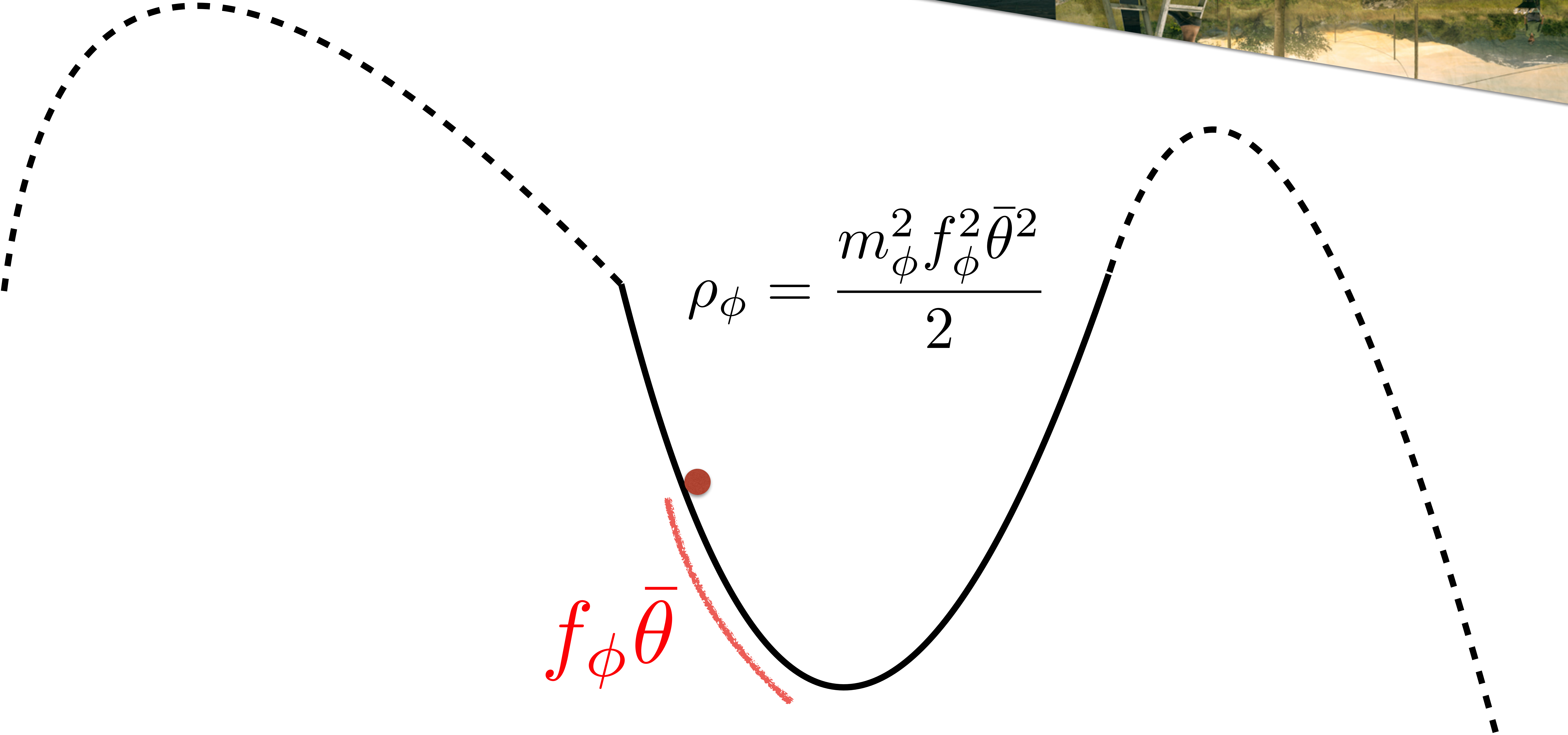
$$\frac{V(\phi)}{V_{\phi H}(\phi, v)} \simeq 1$$

$T \simeq 100\ \mathrm{GeV}$

$T \simeq 100\ \mathrm{MeV}$

$$\Delta\phi$$

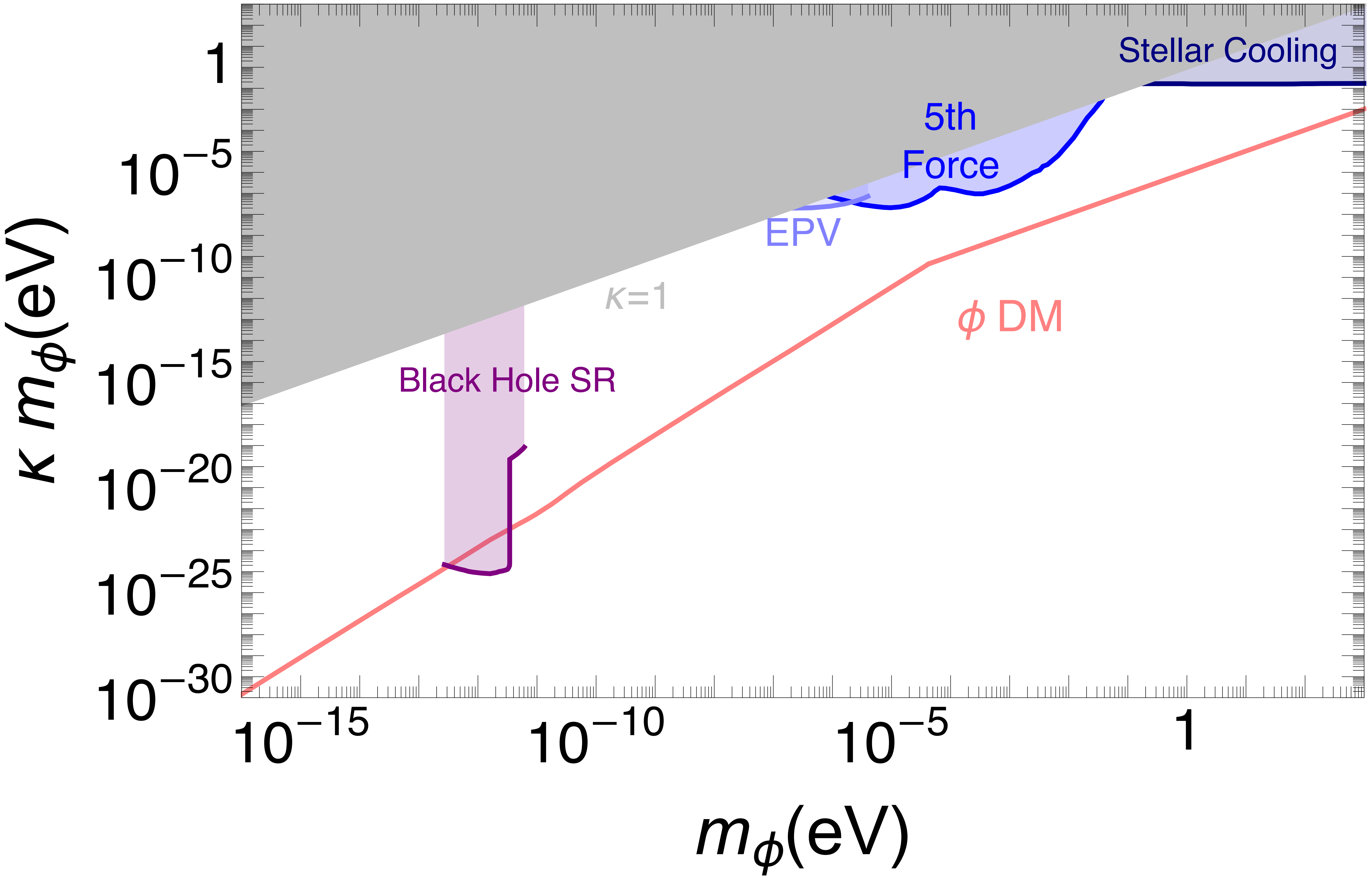
Maximal Displacement from the minimum



“Ultralight WIMP Miracle”

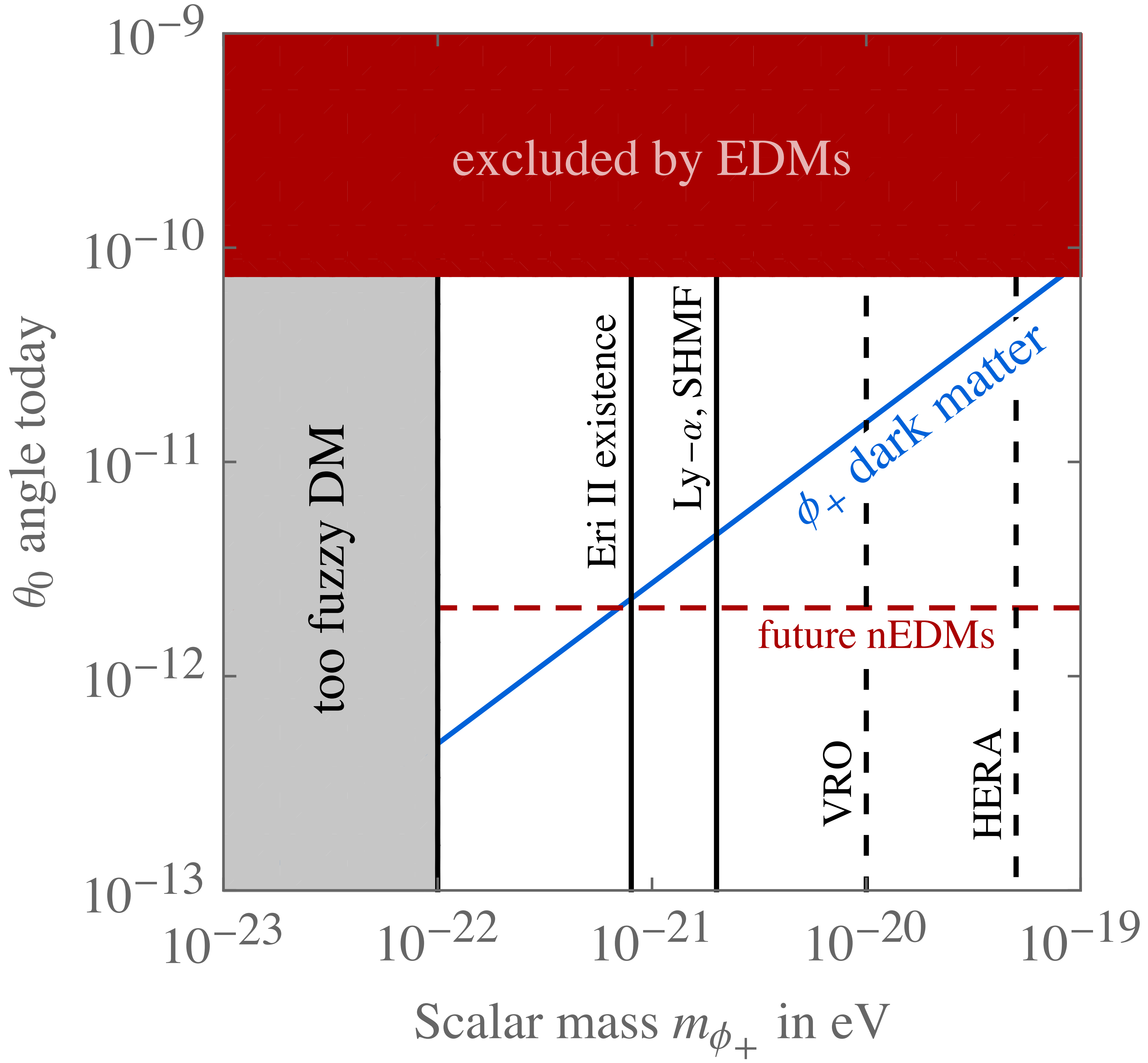
$\phi H_1 H_2$

Ultralight Scalar Dark Matter



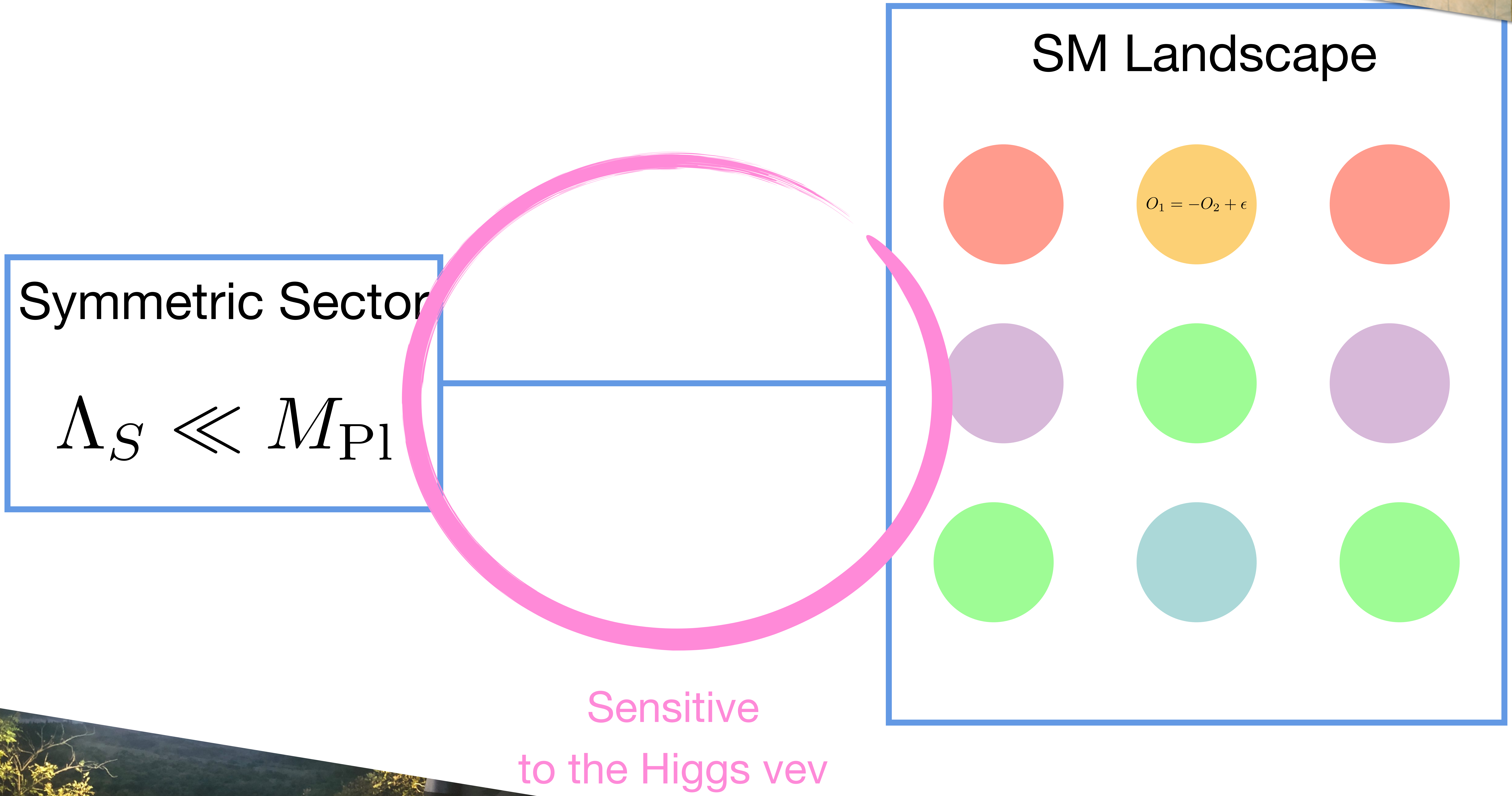
[Arkani-Hamed, **RTD**, Kim, '20][**RTD**, Teresi '21]

Axion-Like Dark Matter



[**RTD**, Teresi '21]

$\phi G \widetilde{G}$

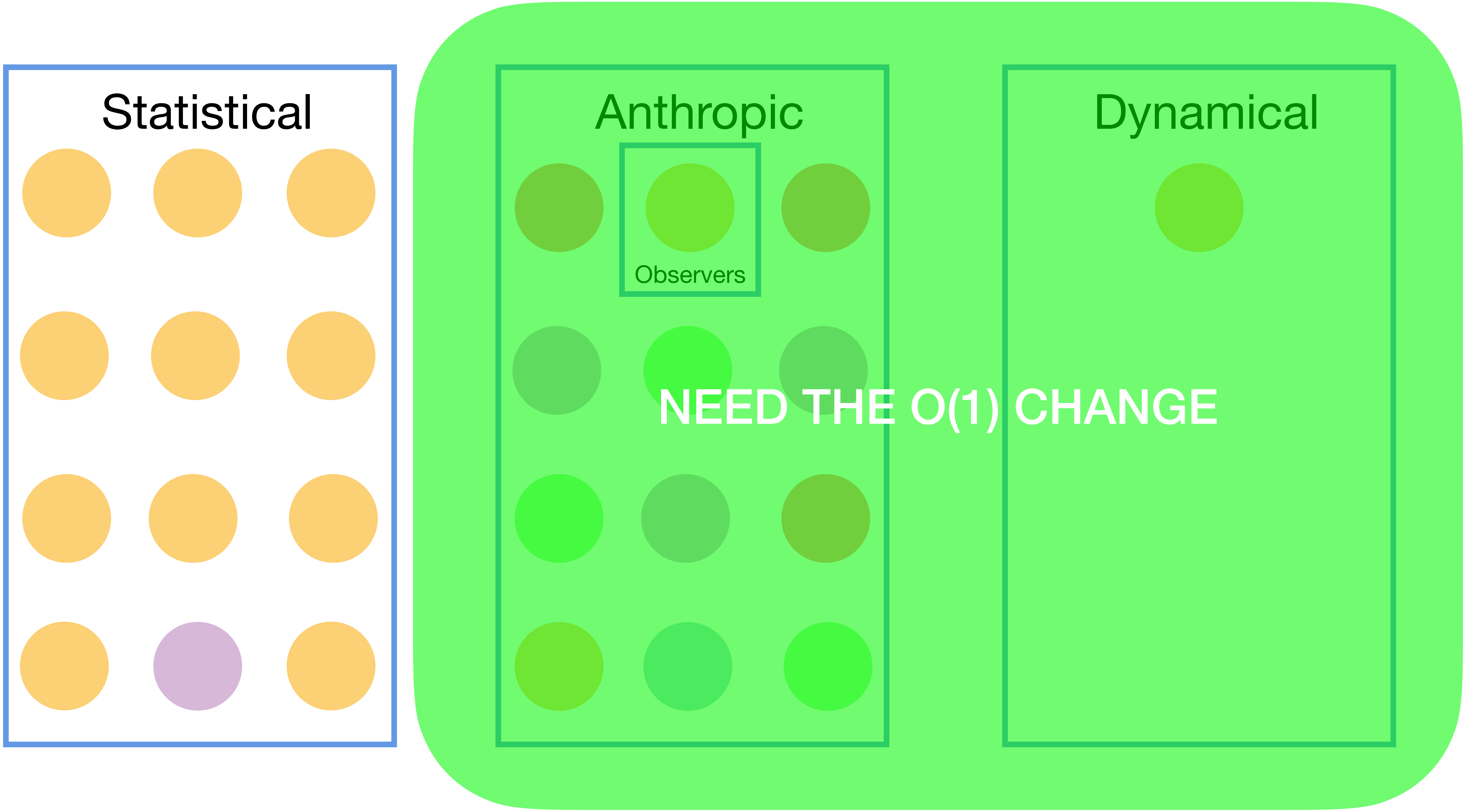

Symmetric Sector
$\Lambda_S \ll M_{\rm Pl}$
SM Landscape
$O_1 = -O_2 + \epsilon$
Sensitive
to the Higgs vev

PART 3: GOING BEYOND COSMOLOGICAL SELECTION

[Arkani-Hamed, RTD, Kim, '20]

Does anything change in Nature as we vary the Higgs mass squared?

$$\frac{d \log f(\langle h \rangle)}{d \log \langle h \rangle} = O(1)$$



Statistical
Anthropic
Observers
Dynamical
NEED THE O(1) CHANGE

Does anything change as we vary the Higgs mass?

LOCAL

$$\mathrm{Tr}[G \wedge G] \equiv G\widetilde{G}$$

NON-LOCAL

On-shell N-point functions of massive SM particles

Does anything change
as we vary the Higgs mass?

LOCAL

$$\mathrm{Tr}[G \wedge G] \equiv G\widetilde{G}$$

NON-LOCAL

On-shell N-point
functions of massive SM
particles

Atomic Principle [Agrawal, Donoghue, Barr, Seckel '97]

Nnaturalness [Arkani-Hamed, Cohen, **RTD**, Hook, Kim, Pinner '16]

Selfish Higgs [Giudice, Kehagias, Riotto, '19]

$G\widetilde{G}$

ALPs

$F\widetilde{F} + yLHE^c$

$m \lesssim v \simeq 174 \text{ GeV}$

HL-LHC!

$H_1 H_2$

$m \lesssim v \simeq 174 \text{ GeV}$

HL-LHC!

$$\langle G\widetilde{G}\rangle \simeq (y_u + y_d)\langle h\rangle f_\pi^3(\langle h\rangle)\theta$$

QCD Theta Angle

Symmetry ~ 10^{10} Experiment

$$\theta$$

Higgs Mass Squared

Symmetry~10^{34} Experiment

$$m_h^2 |H|^2$$

$$\langle G\widetilde{G}\rangle \simeq (y_u + y_d)\langle h\rangle f_\pi^3(\langle h\rangle)\theta$$

Non-trivial!

1. $U(1)_A$ breaking that can interfere with QCD instantons

2. Sensitivity to the Higgs mass ($U(1)_A$ breaking and/or SU(3) running)

3. $\Lambda_{\rm QCD} \lesssim m_h$

First Joint Solution to the two Problems [RTD, Teresi '21]

INSTANTONS

$$\phi \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

$$V(\phi) \sim \int_0^\infty \frac{d\rho}{\rho^4} e^{-\frac{8\pi^2}{g^2(\rho)}} \times \ldots$$

Approximate scale invariance of gauge theory = big hierarchy of scales

EXAMPLE: SU(2) CONSTRAINED INSTANTONS

SM

$$W\widetilde{W}$$

Not observable

EXAMPLE: SU(2) CONSTRAINED INSTANTONS

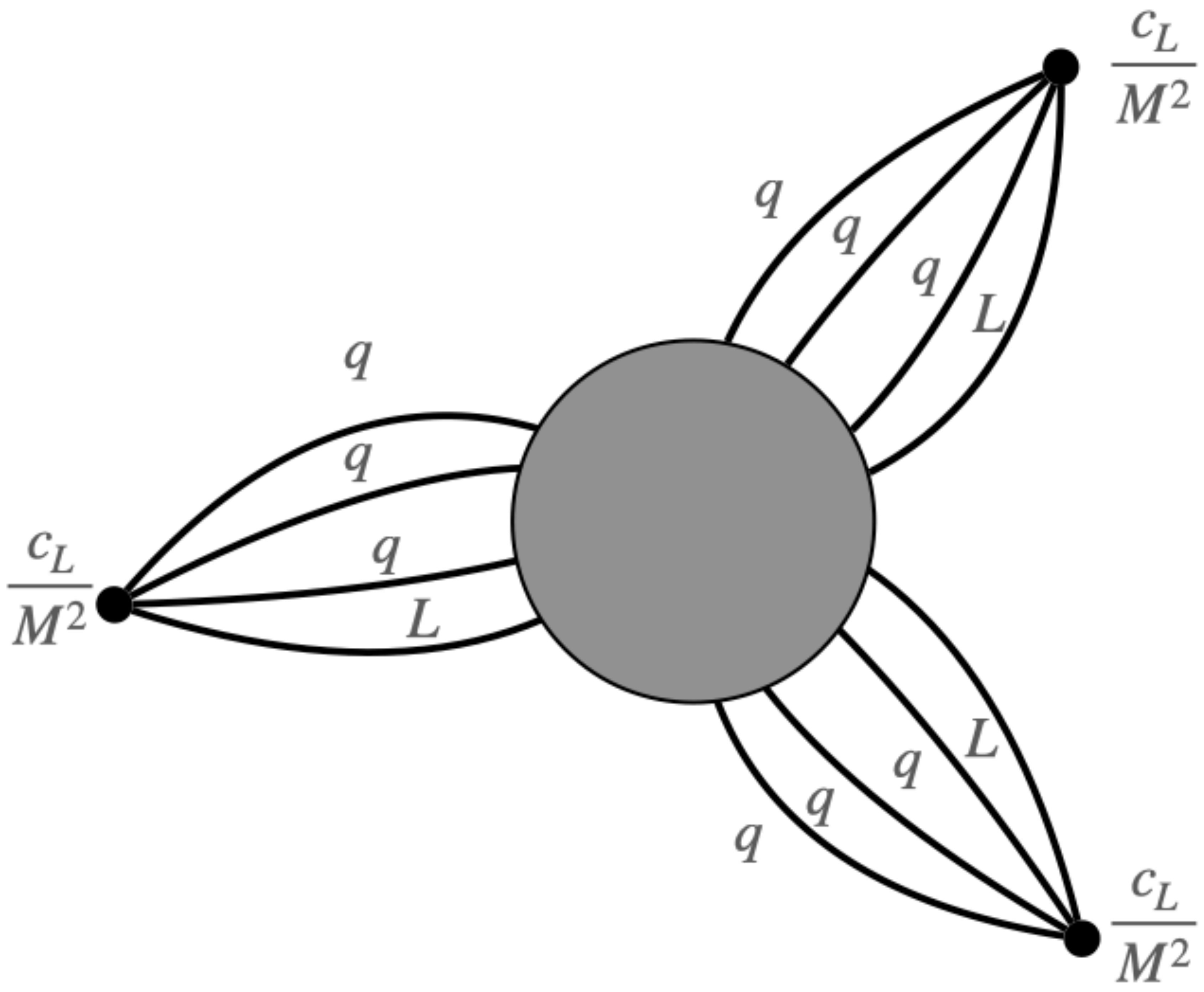
SM

$$W\widetilde{W}$$

Not observable

SM+GUT

$$W\widetilde{W} + \frac{QQQL}{M^2}$$



EXAMPLE: SU(2) CONSTRAINED INSTANTONS

$$W\widetilde{W} + \frac{QQQL}{M^2}$$

$$V(\phi) \sim \frac{\langle h \rangle^{10}}{M^6} e^{-\frac{2\pi}{\alpha_2(\langle h \rangle)}} + M^4 e^{-\frac{2\pi}{\alpha_2(M)}}$$

Tantalizing T=0 connection between B+L breaking and Higgs mass

INSTANTONS IN THE MULTIVERSE

[C. Csaki, RTD, E. Kuflik, in progress]

EXAMPLE:

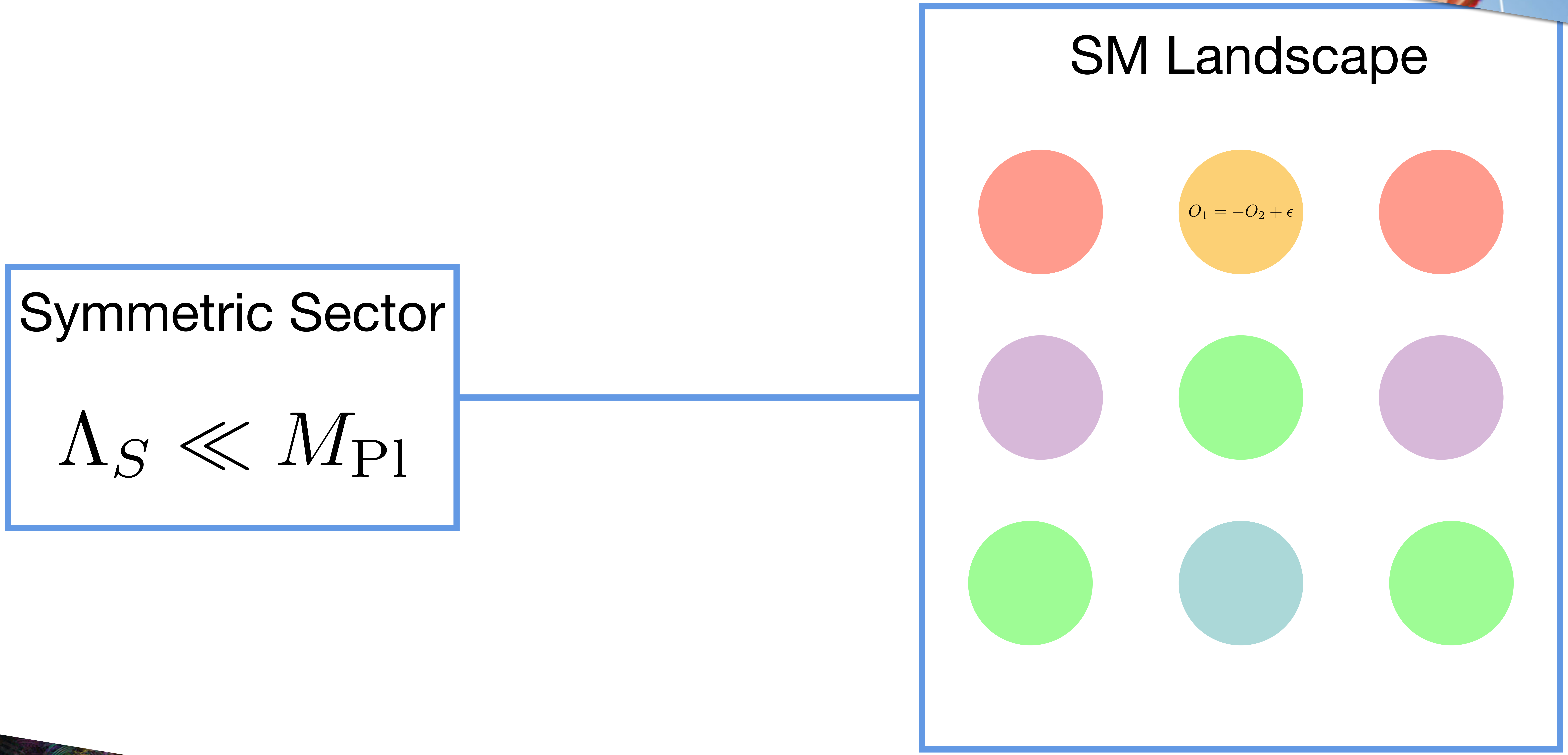
DOUBLET-TRIPLET SPLITTING

HIERARCHY PROBLEM

STRONG CP PROBLEM

in one go!

$\phi F_5 \widetilde{F}_5$ +[RTD, Teresi '21]


Symmetric Sector
$\Lambda_S \ll M_{\rm Pl}$
SM Landscape
$O_1 = -O_2 + \epsilon$

Well-established theoretically

Tons of new signatures and unexpected physics

Symmetric Sector

$$\Lambda_S \ll M_{\mathrm{Pl}}$$

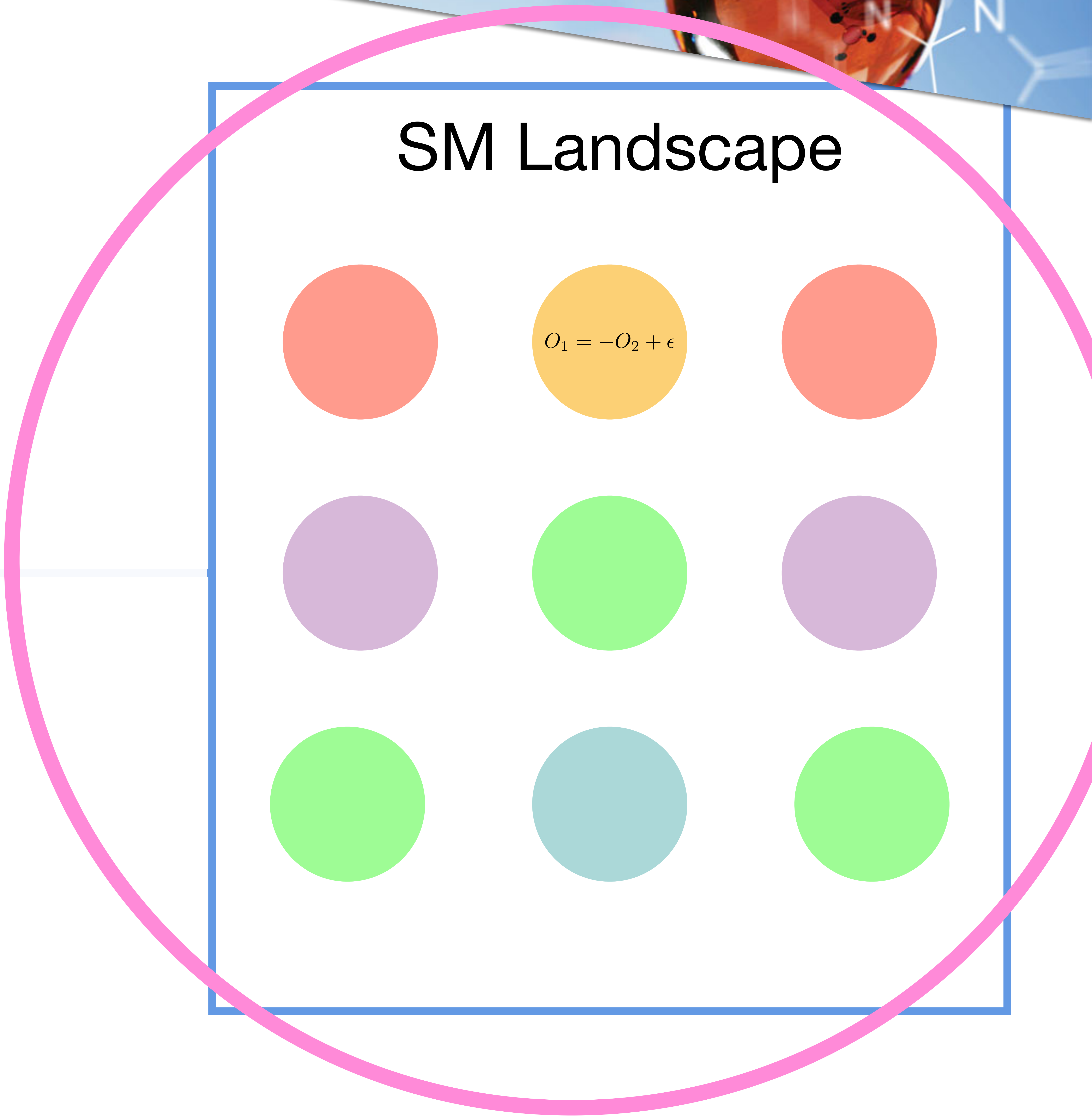
SM Landscape

$O_1 = -O_2 + \epsilon$

Symmetric Sector

$\Lambda_S \ll M_{Pl}$

Forces us to ask hard questions: how does quantum gravity play with inflation, dS and AdS minima, …



BACKUP

ASSUMPTIONS = SOLUTIONS

1. The Higgs mass is ultimately calculable

2. No new symmetries exist below the Planck scale

3. We have extrapolated the Planck mass from low energy measurements

4. We have implicitly treated quantum gravity as an ordinary quantum field theory where high energy particles can leave only very specific imprints at low energy.

$$m_h^2 = 0$$

Special

Planck

New Symmetry

SM

$$m_h^2 \sim \frac{y_t^2 M_S^2}{16\pi^2}$$

M_S

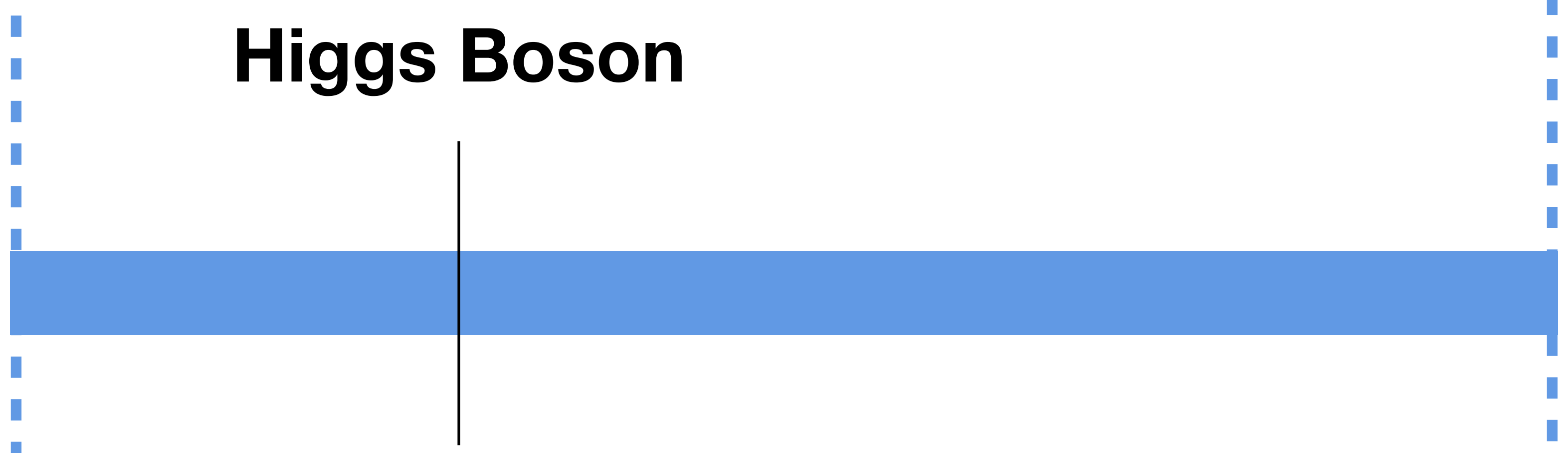
Planck

New Symmetry

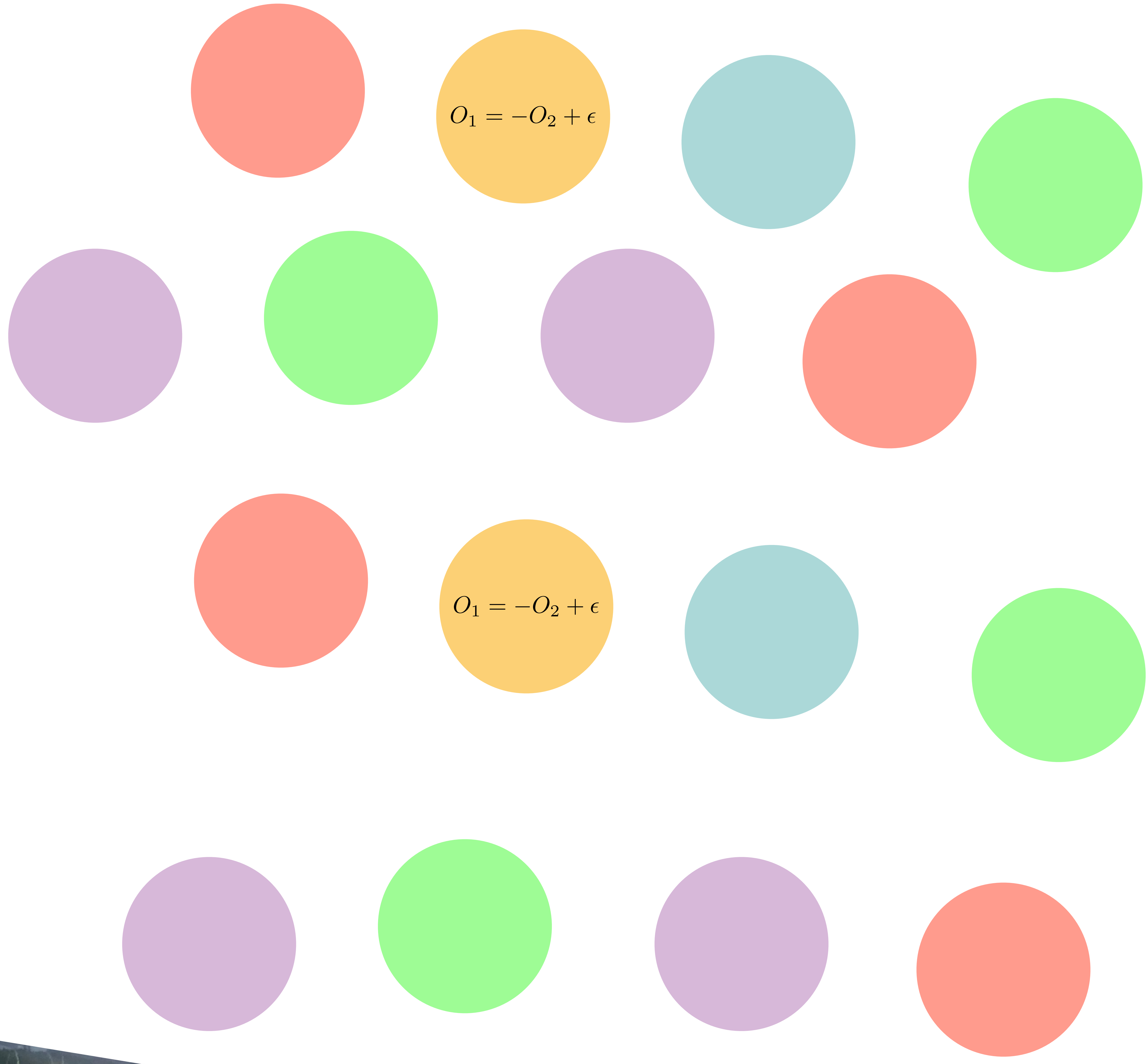
SM

$$\left(m_h^2 |H|^2\right)$$

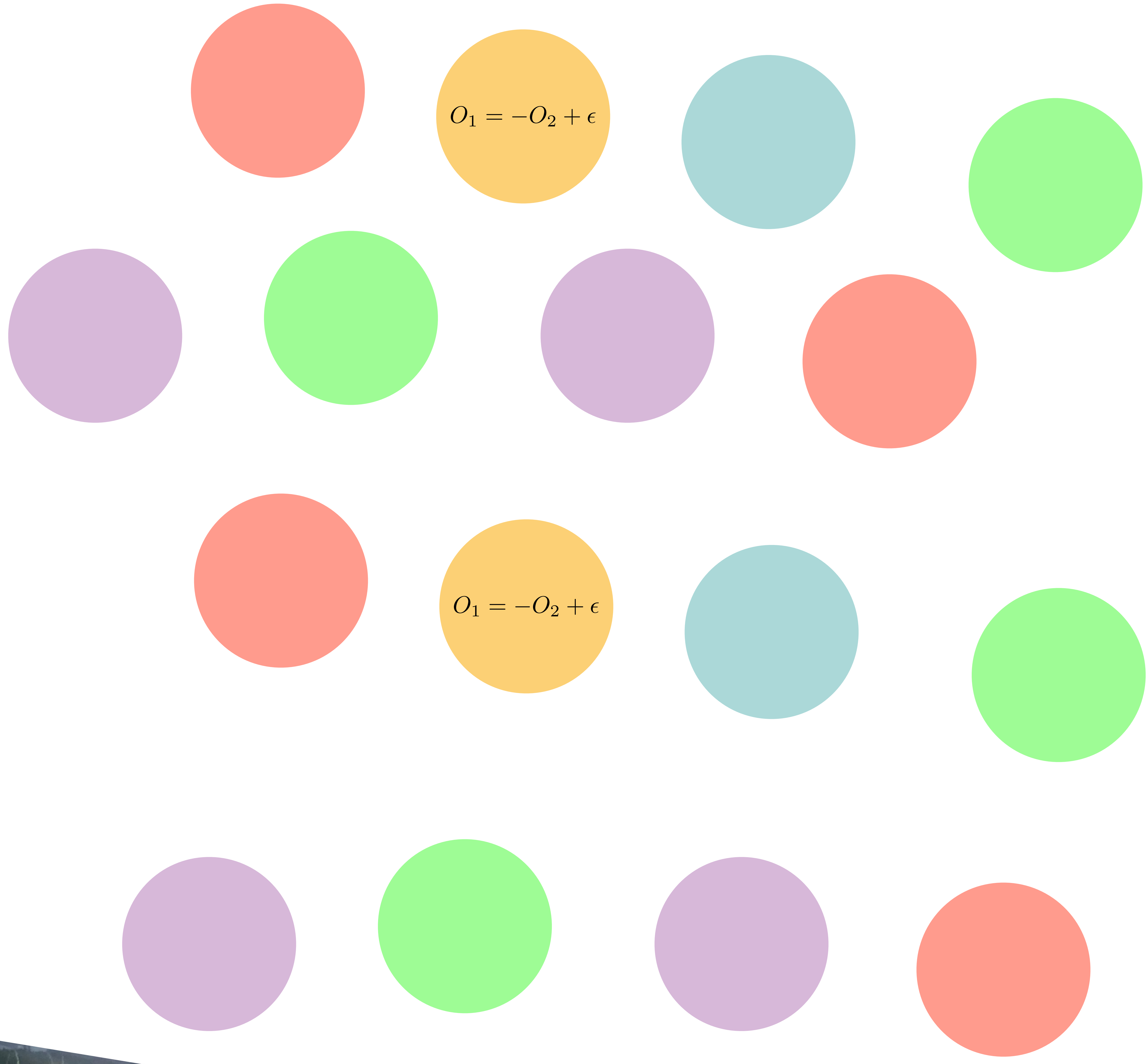
We have been looking for answers at energies close to mh for more than **40 years**



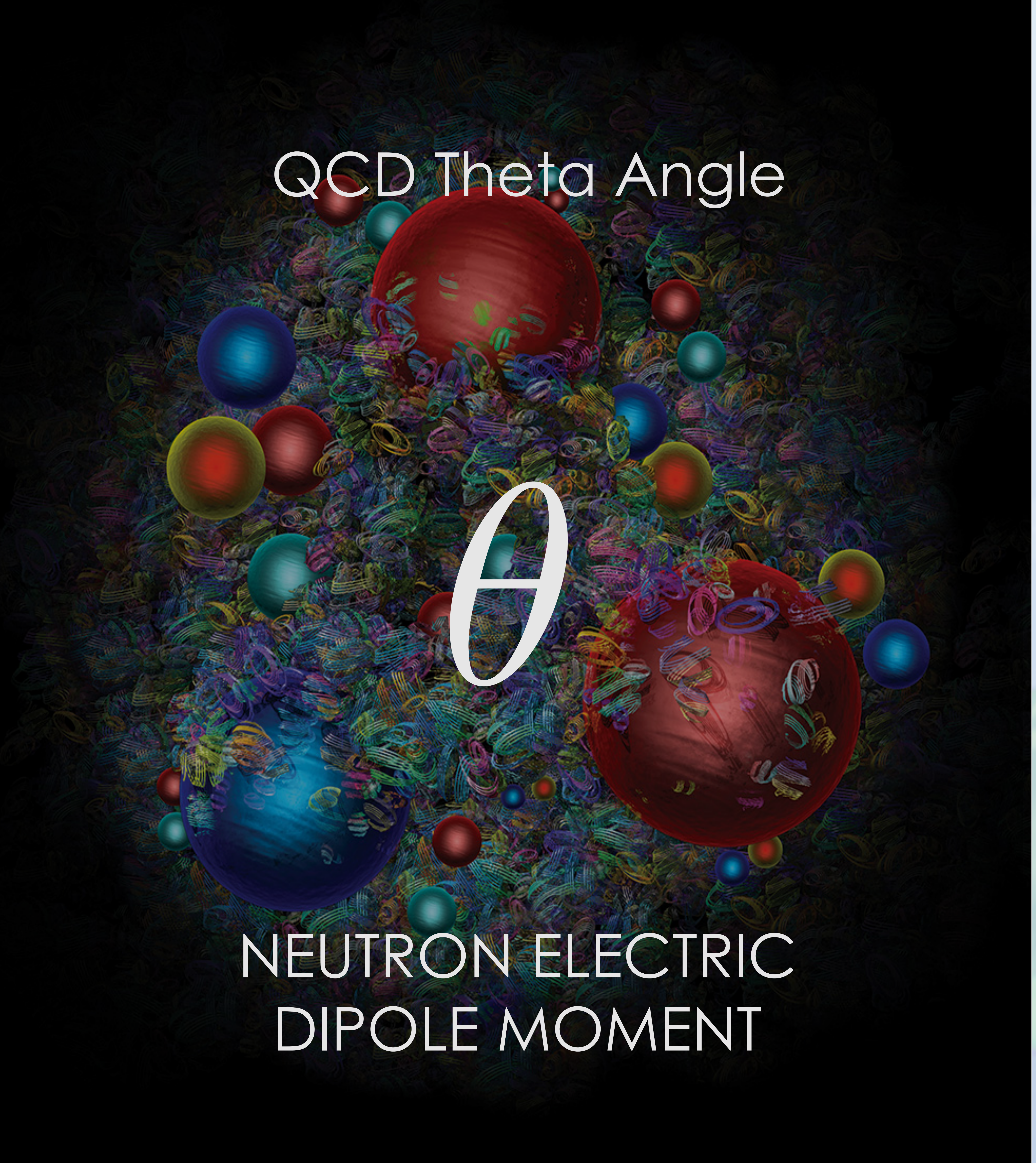
and we have not found them

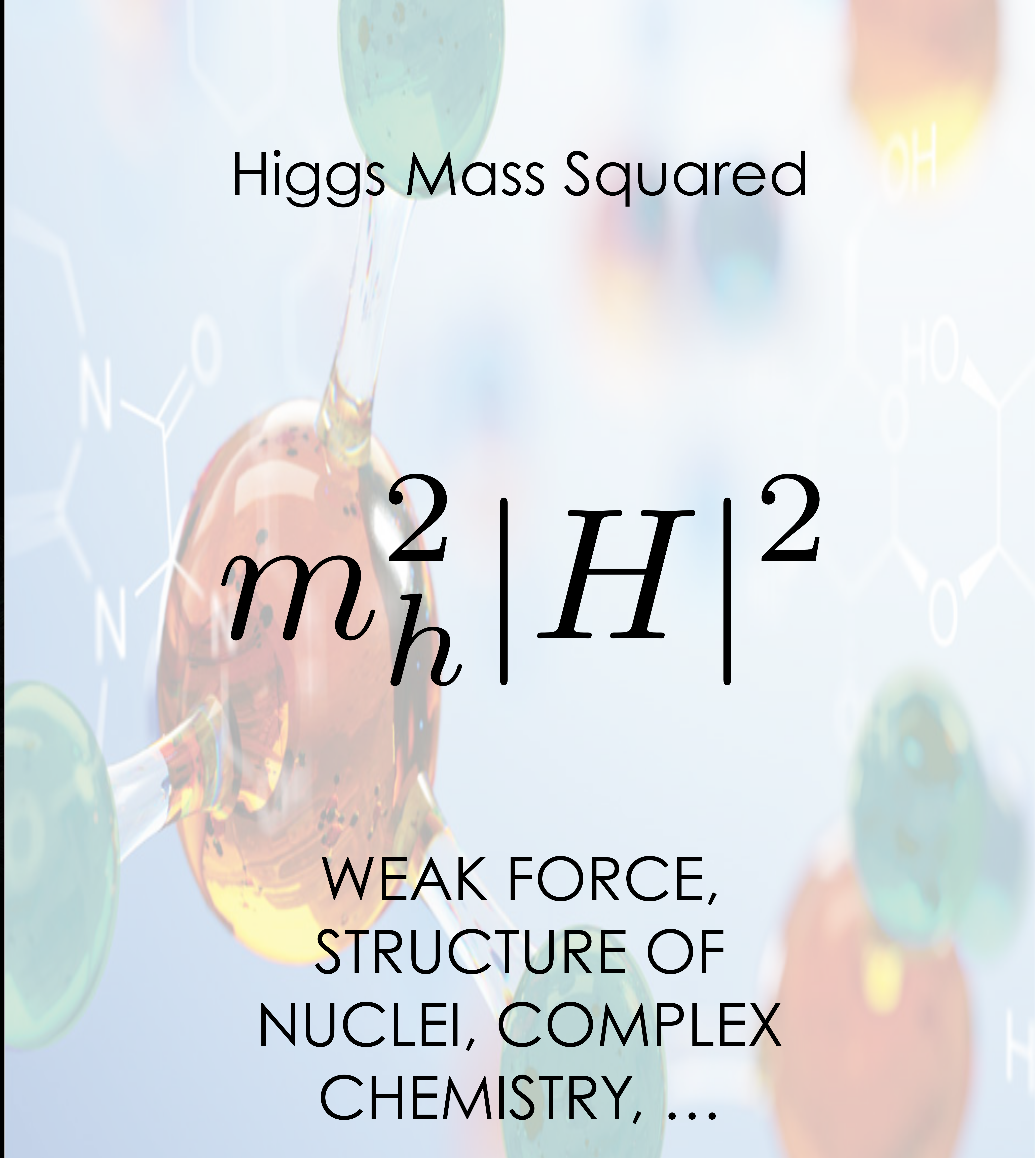


Causally Disconnected Universes with different values of the Standard Model parameters, populated by eternal inflation



1. One day it can be tested experimentally
2. Currently our most concrete explanation for the cosmological constant
3. It might exist independently of the problem


QCD Theta Angle
θ
NEUTRON ELECTRIC DIPOLE MOMENT


Higgs Mass Squared
$m_h^2|H|^2$
WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, ...

QCD Theta Angle

$$\theta \sim \mathcal{O}(1)$$

SYMMETRY-BASED ESTIMATE

Higgs Mass Squared

$$m_h^2 \sim \frac{y_t^2 M_{\mathrm{Pl}}^2}{16\pi^2}$$

SYMMETRY-BASED ESTIMATE

[Arkani-Hamed, RTD, Kim, '20]

$$H_1 H_2$$

Protected by the **Z2 symmetry**

$$H_1 H_2 \to -H_1 H_2$$

H1H2 **without Z2** first considered as 'paleo'-trigger in: [Espinosa, Grojean,Panico, Pomarol, Pujolas '15], [Dvali, Vilenkin '01]. Today these models require **two coincidences of scales to be alive at the LHC**.

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, ’20]

$$V_{H_1 H_2} = m_1^2|H_1|^2 + m_2^2|H_2|^2 + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4$$
$$+\lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1 H_2|^2 + \left(\frac{\lambda_5}{2}(H_1 H_2)^2 + \text{h.c.}\right)$$

$$H_1 H_2 \left(B\mu + \lambda_6|H_1|^2 + \lambda_7|H_2|^2\right)$$
$$B\mu = \lambda_{6,7} = 0$$

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

$$m^2_{A,H^\pm} \sim \lambda v^2, \quad \lambda \lesssim 2$$

$$m^2_H \sim \lambda_1 v_1^2 \leq m_h^2 = (125 \text{ GeV})^2$$

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

For quarks and leptons we choose the **phenomenologically safest Z2 charge assignments**

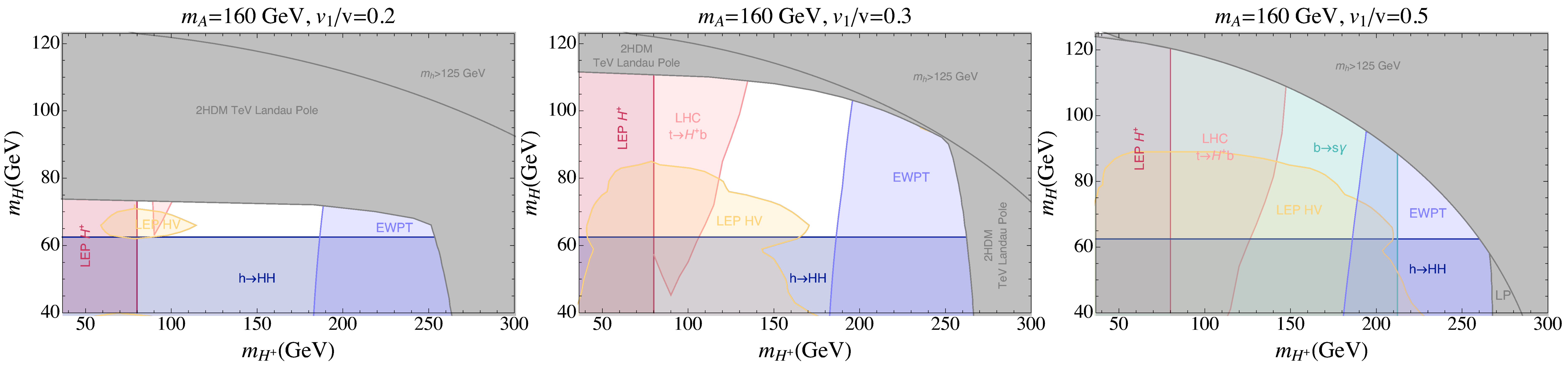
$$H_2 \to -H_2, \quad (qu^c) \to -(qu^c), \quad (qd^c) \to -(qd^c), \quad (le^c) \to -(le^c)$$

This gives

$$V_Y = Y_u q H_2 u^c + Y_d q H_2^\dagger d^c + Y_e l H_2^\dagger e^c$$

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]



Sharp target for HL-LHC and FCC
which **can't be decoupled**!
(See also the next slide)

[Arkani-Hamed, RTD, Kim, '20]